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REPORT AND COMMENTARY ON A SYMPOSIUM ON THE ASSESSMENT AND VERIFICATION OF STATISTICAL AND OTHER SOFTWARE, HELD AT IMPERIAL COLLEGE, LONDON ON 19 DECEMBER 1973

By J. M. CRADDOCK

Summary. The views of several experts on the assessment and validation of computer software are summarized, with comments on their application to meteorology. A selective library of numerical algorithms, improved methods for program development, and an exchange of information on the computing problems of individual groups of meteorologists are suggested as topics worth following up.

Introduction. On 19 December 1973 I attended a Symposium held under the joint auspices of the Royal Statistical Society and the British Computer Society on the Assessment and Verification of Statistical and other Scientific Software, and organized by Dr John Nelder, Head of the Statistics Department at Rothamsted Experimental Station. The discussions produced many points of interest to meteorologists who have to cope with software problems, and enough useful leads to justify the publication of a report on the Symposium in a meteorological journal. I have tried first to give a fair report on the proceedings, and then to suggest lines which sooner or later should result in more useful work being done in less time.

The Symposium. The Symposium was chaired by Mr W. Buckland, of the Economics Intelligence Unit, and was attended by about 200 people, including members of both sponsoring Societies, the universities, the Government Service, and industry. It lasted from 10.30 a.m. to 4.30 p.m. with breaks for lunch and tea, and consisted of four invited contributions, taken in pairs, followed by a Panel discussion. In view of the industrial troubles on the railways, which could have prevented some participants from getting home, the sessions were kept to a strict time-table, which meant that some of the contributions had to be shortened.

After the Chairman's opening remarks, Dr J. Nelder, introducing the main business by speaking on 'A user's guide to the evaluation of packages and systems', stressed the importance of having a proper description which the

customer could consider and assess before deciding whether to buy. With systems, there are three main dangers:

(a) The system may not do what the description says.

(b) It may be capable of misuse in the hands of customers who treat it as a 'black box'.

(c) It may in practice force the user to apply unsuitable methods of analysis to his data.

As speaker, Dr Nelder's task was to arm the user to ask awkward questions of the right people. One question to settle is how the system is driven. A system can be one of two kinds, namely (a) a *translation* system, in which the user's source coding, written in a problem-orientated language, is translated into a universal language (such as FORTRAN or ALGOL), the result being compiled and link-edited with the main coding of the package to produce the object code which the computer will obey, or (b) an *interpretative* system, in which the user's coding in the problem-orientated language remains in being in the computer during run time, albeit in a somewhat modified form, the orders being recognized and interpreted before being carried out by means of the main coding provided by the system. There is something to be said for both types, but GENSTAT, which is Dr Nelder's main contribution to the subject, is an interpretative language. (*Author's note.* The Systems Development Branch of the Meteorological Office has a copy of the GENSTAT documentation, with examples, obtained from the Edinburgh Computing Centre, which deals with its implementation for IBM machines. Users of ICL machines should refer to Rothamsted Experimental Station.) After the question of the preferred type of language has been considered, the question of extensibility comes next. Some means by which the user can extend the system either temporarily or permanently is essential. Facilities for branching, which allow the user to vary the course of the computation, or to repeat certain sections, are also necessary.

After extensibility and branching facilities, the next point to examine is the treatment of data structures. What types of structure can be handled by the system, and how are they treated? Most systems provide for the rectangular matrix, which is the most important, but others are also useful.

In agricultural problems, rows correspond to the data for one case, which may be of several kinds, e.g. numerical measurements, integer variables, and qualitative variables or classifications, while columns consist of values of one variable for different cases. The main advantage of storage by columns is that since the items in columns are all of one kind, they can often be packed more closely than is possible with storage by rows. However, storage by rows is generally preferable, and in GENSTAT the ability to manipulate data in columns when desired is provided by allowing several consecutive rows of the matrix to be worked on at the same time.

After the data structures, the algorithms of the system should be examined, and answers obtained to the questions, 'Do they work?' and 'Do they do what is wanted?' In particular, the treatment of missing and incredible observations should be considered, since, for example, one wrong observation in the data used for a regression analysis may produce a ridiculous result.

On the question of documentation, Dr Nelder stressed the importance of documentation at several levels. (The GENSTAT documentation includes a

manual, many illustrative examples, instructions for whoever is running the program, and some training instructions for users.)

Dr J. Larmouth, Senior Systems Programmer at the Cambridge University Computer Centre, then spoke on 'Validating programs'. His advice, as summarized in a hand-out which included a small test program, is:

(a) Choose the language carefully and read the standard.

(b) Put all documents, including the preliminary design concepts which you have before getting down to detail, in machine-readable form, as these are likely to be lost sight of as the system develops.

(c) Make more remarks about global information than about local information.

(d) Make formal remarks rather than informal, and structure the comment.

(e) Carry out random testing, e.g. on numbers produced by a random-number generator, but keep and distribute the data and the results.

(f) Carry out complete testing, going along each path from every possible branching point, and keep the data and results. It may happen that some paths from some points cannot be traversed in any circumstances, and can be omitted without loss.

(g) Add to the comments when editing. Keep cross-references up to date.

(h) When producing a version of the system for another computer, generate a copy of the existing version, of which the virtues and vices are known. Do not produce an edited version which may misbehave in some completely novel way.

Dr Larmouth then examined his test program, and showed that it can be proved correct, in the same way that a theorem in Euclidean geometry can be proved.

In the discussion Mr I. D. Hill (Medical Research Council) remarked that Dr Larmouth's test program would not compile in the form printed, and he and various other speakers cast doubt on the practicability of 'complete' testing. Mr Craddock said that although 'correctness' in Dr Larmouth's sense was a virtue in a program, it was neither a necessary nor a sufficient condition for the program being the most suitable for a given job. If a job is being repeated regularly, so that any result which falls outside the usual pattern is immediately suspect, a simple program which gets the right answers 99 per cent of the time may be more effective than a more elaborate one which rarely fails, but which takes up more space or time. Certainly, if provision is made for the abnormal situation, such as coincident eigenvalues, then the coding should be tucked away in a drum segment from which it can be fetched when required, and not kept permanently in core. To Dr Nelder he suggested that besides the questions given, the user should, with reference to the space required by the system, also ask:

(a) What is the total space needed for the coding?

(b) How is this divided between administrative coding, which would be required equally in a system with some quite different purpose, and executive coding, which has a recognizably statistical content?

(c) How readily can the coding be segmented to suit the individual computer?

(d) How readily can the system be dismantled to get at the few per cent which seems likely to be useful in a new environment?

(e) How can the coding be interfaced with the customer's own software?

Dr Nelder replied that space requirements were important, and that, given more time, he would have dealt with them. In answer to the last point he said that the best way to interface with the GENSTAT system is to 'output' the data from the meteorological or other software in a form which GENSTAT will accept as input. There should be no great difficulty in doing this. (On reading the GENSTAT literature since the Symposium, I am sure that Dr Nelder is right. GENSTAT is not really adapted for run-of-the-mill meteorological data processing, whereas any meteorologist who wishes to experiment with any of the advanced statistical techniques which it provides should consider whether he can use it. It may easily save him the most frustrating part of his task.)

Mr G. B. Hey (Co-operative Insurance Co. Ltd) said that the methods of validation discussed by Dr Larmouth showed no change from those which he had used, when working with the late L. J. Comrie in 1935, for verifying complicated plugboards on Hollerith machines. In commercial work which involved receipts and payments, and legal obligations, accuracy under every set of circumstances which could arise in real life was most important, and was very rarely achieved, in computer software supplied either by manufacturers or by others. His Company maintained a special test file for use with any new software, which had to reproduce results known from previous analyses before the software was passed as fit for use.

After lunch Mr B. J. Ritchie (Staff Manager, Computer Analysis and Programmers (Reading) Ltd) spoke on 'The verification of complex scientific packages', with reference to a package recently completed for testing an airframe without destroying it, by the application of computer-controlled stresses by means of hydraulic jacks placed against various points in the frame. He said that methods of *proving* the correctness of programs are still in their infancy and are applicable only to logically trivial problems. Today's software professionals therefore adopt the less formal but equally rigorous approach of *testing* their products against predefined criteria dependent upon the application itself. This approach requires that programs be structured in ways which permit the use of software *test tools* throughout all stages of development, and the cost of producing these tools may form an important fraction of the total cost of the software. Great emphasis is placed on building *robust* systems, in which hardware or software failures must be localized. The conceptual planning stage, in which the system is outlined before any detailed coding takes place, is most important and cannot be hurried. 'You cannot produce a baby in one month by putting nine women on the job'.

Dr Brian Ford, Chairman of the Numerical Algorithms Group Project, Oxford University Computing Laboratory, then spoke on 'The assessment and verification of software for a general-purpose numerical algorithm library'. He said that the library was intended for the general users of a university computing laboratory, and that unlike many such projects which set out to include every example of coding published, the Numerical Algorithms Group Project intended to be selective, and to keep only a few of the best programs suitable for dealing with specific problems on computers of all the types likely to be

used. They had a library of about 250 programs covering most aspects of numerical analysis, with the exception of the solution of partial-differential equations, for which they had no suitable contacts. These programs were being tested or adapted for six different types of computer, and as far as possible, common standards of accuracy and documentation were maintained for each type of computer. The programs were issued in semi-compiled form, being copies from the master source file, and information on any failures was to be fed back to the group, who would be responsible for analysing the failures and correcting the master file. They had a precisely specified subset of FORTRAN, which, as far as was known, was interpreted in the same way on all the types of computer. They hope to distribute tested mathematical software, with information on:

(a) Algorithm performance, from the point of view of
    (1) Elementary arithmetic.
    (2) Function evaluation.
    (3) Function approximation.
(b) Robustness.
(c) Numerical stability.
(d) Speed.
(e) Region of effectiveness.
(f) Efficiency.
(g) Portability.

Some algorithms are contributed by members of the group, while others are produced at the centre. Of the contributed algorithms, not one has produced the same identical answers under test on each of the six families of computer. Differences between answers can arise if the algorithm is unstable or if the problem is ill-conditioned, and differences between families of computer can arise through differences in the input data, or in the conversion from decimal to binary, or in the round-off. The coding itself could conform to one of three standards: coding with redundancy, coding without redundancy, and structural programming, as conceived by Professor Dijkstra.

In the discussion on these papers Mr Craddock remarked that as the Meteorolocial Office IBM 360/195 computer spent a large part of its working life solving partial-differential equations, there must be scientists within the Office with the know-how needed to fill some of Dr Ford's gaps in this field. On the other hand a selection of algorithms which have been chosen by experts on topics outside meteorology, and which can be obtained when required, could be most useful to any meteorologist wishing to venture outside his own field. He therefore asked:

(a) Has the Numerical Algorithms Group a specification for its Universal FORTRAN?
(b) Is there any document giving the address and full description of the group?
(c) Is there a list of the algorithms tested so far?
(d) Is there a subscription for joining the group?

In reply, Dr Ford said that so far they had not quite reached the stage of organization implied by these questions, but that they were always willing to discuss the software with scientists concerned with the subject. A lively discussion followed.

After the tea break, a Panel which included the main speakers answered questions propounded by the audience, or by themselves. While the discussion cannot be reported in detail, the following are some of the main points:

Dr Larmouth said that despite appearances, verification techniques *had* advanced since the 1930s. In the discussion on this subject, it appeared that nobody was very enthusiastic about the prospects of proving programs correct by logical process, as opposed to checking their performance by applying them to previously analysed test data.

The question of the transferability of programs was raised, and there was some good-humoured banter about whether Cooper's ASCOP (A statistical computer procedure) was worth the fee asked for it by the National Computer Centre. The answer seems to depend on whether the prospective purchaser expects to use nearly all the system, or only a small part.

Mr I. D. Hill mentioned that the efficiency of the object program produced from a high-level source program depended to a considerable extent on the compiler used, but the subject was not taken up.

The problem of keeping track of a computation while developing complicated software was raised, and Mr Craddock remarked that for any computer with the DEBUG feature provided by the IBM FORTRAN G compiler, an efficient solution consists in having a special integer variable, e.g. JEST, which is used purely for tracking and diagnostic purposes. When the DEBUG feature is in use for this variable, any assignment statement such as JEST = 999, JEST = NZ(73) produces a diagnostic print JEST = (the numerical value assigned) every time the statement is executed. The rules to be followed in using the JEST variable are simply that no statement including JEST is ever labelled, and that no two assignment statements give the same value to JEST. Thus each printed value of JEST is positive proof that the computation has reached a particular point, and if the tracking assignment statement is followed either by a WRITE statement for some interesting array, or by an assignment setting JEST equal to some interesting variable, the computation can be followed to the desired depth without the production of quantities of meaningless paper. When the testing is complete, all statements involving the JEST variable can be removed without affecting the rest of the computation, except by making it marginally faster. Mr Craddock said that the device is so easy and flexible that since finding it he has hardly used any other, and inquired whether computers of other manufacture had anything equivalent to the DEBUG feature. The question was left unanswered.

The question of documentation was discussed at some length, with the curious result that while all the speakers advocated full documentation, and recommended the users of software to read the documentation thoroughly, they all agreed that few if any users did so. A member of the audience expressed the view that the whole exercise was useless, because although every programmer was willing to look at someone else's software, in the end he preferred to write his own. Nobody produced an answer to this comment on the spur of the moment, and on this rather inconclusive note, the Symposium ended.

Discussion. Nearly all the advice offered was in line with current practice in the Synoptic Climatology Branch of the Meteorological Office, and at the end of the Symposium I was left with the comfortable feeling of M. Jourdain who consulted the professors, and found that he had been talking prose all his life. Many other meteorological programmers would probably have reached the conclusion that no great changes are called for in their present methods, but suggestions were made under three headings which, if properly exploited, could enable meteorologists to do more useful work in less time, or at lower cost. These are:

(a) Suggestions for a selective library of algorithms on specific topics, as outlined by the Numerical Algorithms Group.

(b) Advice for improving the technique of developing effective computer programs, from Dr Larmouth and Mr Ritchie.

(c) Advice on the choice of software systems (which are specialized computer languages) or packages (which are families of matched subroutines) as discussed by Dr Nelder.

The topics are discussed individually below.

The sum total of published algorithms, including the packages provided by the computer manufacturers, and those published in the *Communications of the Association for Computing Machinery*, *Numerische Mathematik*, the *Journal of Applied Statistics* and elsewhere, not to mention the semi-published algorithms which circulate among scientists, are numerous enough to deter any scientist who looks outside his own field of expertise. If, for example, a meteorologist conceives a technique which at some stage involves finding the complex roots of a polynomial, he can spend a disproportionate amount of time reading about the subject, and finding coding to carry out the operation, without any guarantee that he will arrive at an efficient and stable solution. Conversely, a scientist unfamiliar with the solution of partial-differential equations who attacks the problem without making use of meteorological know-how on the subject runs the risk of wasting a great deal of time on problems which have already been solved. A group which can serve as a central clearing-house for know-how on specific numerical problems, so that any scientist who ventures outside his own field can start from something which corresponds to the best modern practice, could save much duplication of effort, and it seems to me that the work of the Numerical Algorithms Group deserves full co-operation and support.

As regards the development of effective software, the advice of Larmouth[1] seems to me to be almost wholly good, but it is so difficult to obtain hard facts about the time taken by meteorologists to develop software, or the efficiency of the software once it is working, that I can only guess how far the meteorological community is in need of such advice. Points on which I have no doubt are that nearly all programs are under-documented, and that while some groups are so strongly staffed that they should be able to maintain very high standards of coding, and as far as I can judge, succeed in doing so, other groups have to spread their programming talent much more thinly and may have difficulty in improving their software once it fulfils its main purpose. The main limitation of Dr Larmouth's advice is that some of it seems rather high-powered for a good many programmers who, from experience within the Office, are quite

capable of doing useful work, and I suspect that the majority of readers, especially those using an IBM computer, would benefit by reading in addition Kreitzberg and Schneidermann,[2] and Day.[3] However, now that meteorologists have been living with computers for 15–20 years, there must be a good many who have worthwhile thoughts on the techniques which make for an inspiring, or at least a tolerable existence, and it is about time that more of these thoughts appeared on paper.

As regards computer systems and packages, these try to go further than the other proposals towards solving the user's software problems, and deserve to be taken seriously. However, it is clear that much more is needed in the way of free discussion and the exchange of information, before it can be seen whether any system developed outside the meteorological world can be a cost-effective solution to any meteorological need. The need for more information is shown by the facts that Schucany, Minton and Shannon[4] list no fewer than 37 systems and packages concerned with statistics alone, while the meteorological workload, currently running at about 4500 jobs per week, comes from about 20 groups of programmers, most of whom are far too busy solving their own problems to have much time for the cross-fertilization of ideas. The systems that I have examined, however, seem to suffer from at least three disadvantages. A great deal of effort is spent on providing facilities which are unnecessary to meteorologists, either because they are available already, or because there is no demand for them, so that the full cost of the system has to be balanced against the potential value of a small part of the coding; there are features in the working environment of a meteorological office, involving the real-time handling of vast numbers of data as a prelude to elaborate scientific computations, which cast doubt on the applicability of any coding developed in an institution not subject to the same constraints; and in the systems which are good technically, the descriptive documentation seems to be aimed at readers more highly qualified than the staff who would in practice have to use them. Unless these objections can be overcome, I do not rate the prospects of acceptance of any system highly compared with those of the products of the Numerical Algorithms Group.

A further comment, which applies also to software produced within the meteorological world, is that there is no point in a software designer producing a program which is, in his opinion, the perfect solution to a computing problem if he fails to persuade the prospective customer to use it. The psychology of computer users is an intensely interesting subject, the importance of which became evident during the Symposium, and I think that the essential point is that once a programmer has enjoyed the freedom to solve his own problems in his own way (which comes from real fluency in a computer language) he will never willingly surrender that freedom, so that software which in effect restricts his freedom of choice will be rejected out of hand. However, if the software designer is willing to accept the principle that the customer is always right, and simply to provide what is asked for, the prospects of fruitful co-operation are much brighter. This agrees with my own experience, in the Meteorological Office, but the amusing article by Cutbill and Jones[5] suggests that the same tensions also occur elsewhere. However, my purpose at this stage is not to suggest solutions, but simply to argue that the value of computer systems, or more generally of techniques for getting useful work out of a computer, is not

something which can be measured wholly by abstract standards, but must be judged against the needs of real people in a real working environment, and that what is needed at present is more information about working situations, and about the needs which are felt to be pressing by the people in these situations, to provide the systems designers with the material to work on. I suggest that meteorologists in different fields should try to publicize their own software problems, and the working environments which give rise to these problems, by offering contributions either to this journal, or to one more specifically concerned with software.

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MESOSCALE STRUCTURE OF JET STREAMS AND ASSOCIATED CLEAR-AIR TURBULENCE

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Summary. Large-amplitude clear-air 'billow' echoes due to clear-air turbulence as observed by the Defford high-power radar are displayed on time–height sections, corresponding to the passage of five upper-tropospheric jet streams. The occurrence of the billows is discussed in relation to the time–height sections of wind speed, magnitude of the vector vertical wind shear and vertical gradient of potential temperature derived from sequential radiosonde ascents made during the passage of the jet streams.

The Roach Index, Φ, is illustrated for three of the case studies. Large-amplitude billows were detected in regions where $\Phi > 10^{-4}\,s^{-1}$.

Introduction. Theoretical considerations and observations in the laboratory, ocean and free atmosphere suggest that most clear-air turbulence (CAT) is in the form of unstable waves due to Kelvin–Helmholtz instability (KHI) which develops within stably stratified, quasi-horizontal flows in the presence of strong shear. It is well known, too, that CAT is associated with distinctive features in the upper-air flow (Roach[1]) and, in particular, with regions of strong vertical wind shear in the vicinity of jet streams. An analysis of a number of case studies by Browning[2] has shown the relationship between the occurrence of KHI detected by high-power radar and mesoscale atmospheric structure in its immediate vicinity. There is, however, a shortage of data concerning the nature of mesoscale regions of preferred KHI development

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in relation to synoptic-scale features such as jet streams. This paper is seen as an extension to the work of Browning[2] and its purpose is not only to seek to clarify the relationship of large-amplitude Kelvin–Helmholtz (KH) billows to mesoscale features of atmospheric structure (e.g. vector vertical wind shear and vertical gradient of potential temperature) but also to investigate the characteristics and distribution of the mesoscale features in relation to the synoptic-scale pattern.

Terms such as 'strong shear' have a precise meaning throughout the paper and these definitions will now be introduced formally:

weak shear	$\lvert\Delta V/\Delta z\rvert$ less than 5 m/s per 400 m,
strong shear	$\lvert\Delta V/\Delta z\rvert$ between 5 and 10 m/s per 400 m,
very strong shear	$\lvert\Delta V/\Delta z\rvert$ in excess of 10 m/s per 400 m,
weak stability	$\Delta\theta/\Delta z$ between 2 and 6 degC per 400 m,
strong stability*	$\Delta\theta/\Delta z$ between 6 and 10 degC per 400 m,
very strong stability	$\Delta\theta/\Delta z$ in excess of 10 degC per 400 m,
low Richardson number	Ri less than 0·5.

Data acquisition, analysis and presentation. The case studies to be discussed were obtained during the passage of jet streams overhead or nearby. During operational periods, each generally of at least 8 hours' duration, data were obtained by two methods; observations of echoes from clear air by the high-power radar at the Royal Radar Establishment, Defford and soundings from radiosondes tracked by precision radar.

The Defford 107-mm wavelength radar has been described by Watkins.[3] CAT gives rise to turbulent flow on a range of scales down to those smaller than half the radar wavelength and the resulting refractive-index irregularities are detected by the radar. Aircraft penetration of these clear-air echo layers and billows (Glover *et alii*,[4] Glover and Duquette,[5] Browning *et alii*[6] and Mather and Hardy[7]) have confirmed that they are indeed associated with CAT.

In the present study the high-power aerial scanned continuously in the vertical plane from 0° to 90°, into the direction of the upper-tropospheric winds, at the rate of about 1 scan every 2½ minutes. Resulting echoes were displayed and photographed on a conventional Range–Height Indicator (RHI) display. The limit of resolution of the radar in the vertical is typically 100 to 200 m (pulse length 187 m, half-power beam width 0·33° in the vertical and horizontal) and it was only possible to resolve clearly the structure of billows with amplitudes in excess of 200 m. Horizontal trains of billows with much smaller amplitudes were detected as almost featureless layer echoes. Although the resolution and sensitivity of the radar limits the range and height to which very slight CAT due to small-amplitude KHI may be detected, it can reasonably be expected that the radar will detect all large-amplitude billows (i.e., crest-to-trough amplitude in excess of 400 m) associated with at least slight turbulence within a range of about 15 km and lying below a maximum height of 12 km. Hourly radiosonde ascents from the Royal Radar Establishment's Pershore site, 8 km north-east of Defford, permitted good resolution of mesoscale atmospheric structures. Temperature data were evaluated with a maximum resolution obtainable at height intervals of about 100 m, giving an

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* The corresponding $\Delta\theta$ over 400 m for an isothermal lapse is as follows: 4 degC at a height of 4 km; 6 degC at a height of 8 km; 8 degC at a height of 12 km.

r.m.s. error in $\Delta\theta$ of about 0·2 degC. The use of data at 20-second intervals permitted ΔV to be evaluated over height intervals of 400 m with an r.m.s. error usually about 0·5 m/s.

Since a long-term aim of CAT studies is to devise improved techniques whereby routine synoptic-scale radiosonde data supply the input for predicting regions of CAT, the vertical resolution of shear, etc., has been taken over deep layers ($\Delta z = 400$ m). This depth still provides a vertical resolution comparable with the depth of the deeper dynamically unstable layers which are the subject of this study. Of course, the Richardson number (*Ri*) may often be critical over shallow layers while its bulk-value over 400 m is above critical. Correlations of CAT occurrence with estimates of *Ri* based on routine radiosonde observations will therefore be too low except perhaps in the case of KHI which occurs over deep layers.

Results. Figures 1(a–e) illustrate the locations of the observations, AB, made in the vicinity of the jet core on the case-study days, displaced relative to the jet according to the system velocity.

The families of time–height cross-sections, forming the basis of the data presented in this paper, are illustrated in Figures 2–6. Cross-sections are as follows: (a) horizontal wind speed, *V*, (b) magnitude of the vector vertical wind shear, $|\Delta V/\Delta z|$, and (c) vertical gradient of potential temperature $\Delta\theta/\Delta z$. Figures 7 (a–c) show the Roach Index, Φ. This index (Roach[8]) is intended to be a measure of the probability of occurrence of CAT, and has been computed using data from radiosonde ascents. Occurrences of large-amplitude billows with crest-to-trough amplitude in excess of 400 m are represented by crosses in each set of sections. Virtually continuous radar surveillance was maintained so that the absence of a cross can properly be interpreted as indicating the absence of significant large-amplitude billow events in the vicinity of Defford.

(a) *6 February 1970* (10 GMT to 1930 GMT). At low levels a region of high pressure over the southern half of the British Isles receded towards the south-east during the period and south-westerly winds became established. The warm front which preceded a narrow warm sector eventually passed through the Defford area at about midnight. A strong northerly upper flow was maintained over the area throughout the period and was advancing across the British Isles from about 300° at 13 m/s. Observations were made within a region of relatively straight flow between trough and ridge during the passage of the jet from the cold to the warm side (Figure 1 (a)). The section passed into the jet core at 14 GMT and out of it at 1630 GMT. Time–height sections of V, $\Delta V/\Delta z$ and $\Delta\theta/\Delta z$ are displayed in Figures 2 (a), (b) and (c) respectively. An intense KH billow (crest-to-trough amplitude 400 m) occurred at 1243 GMT within the frontal zone in a region of very strong shear, strong stability and low *Ri*. Figure 7 (a) presents the distribution of the Roach Index, Φ. The single large-amplitude billow event was associated with a value $\Phi = 15$ in a region of strong Φ gradient.

(b) *18–19 February 1971* (17 GMT to 05 GMT). Throughout the period a trough lay parallel to and just off the east coast, its southern end curving eastwards towards the centre of a filling depression over the Danish–German border. At low levels west-north-westerly winds over most of England and Wales preceded a warm frontal system approaching from the Atlantic. The main

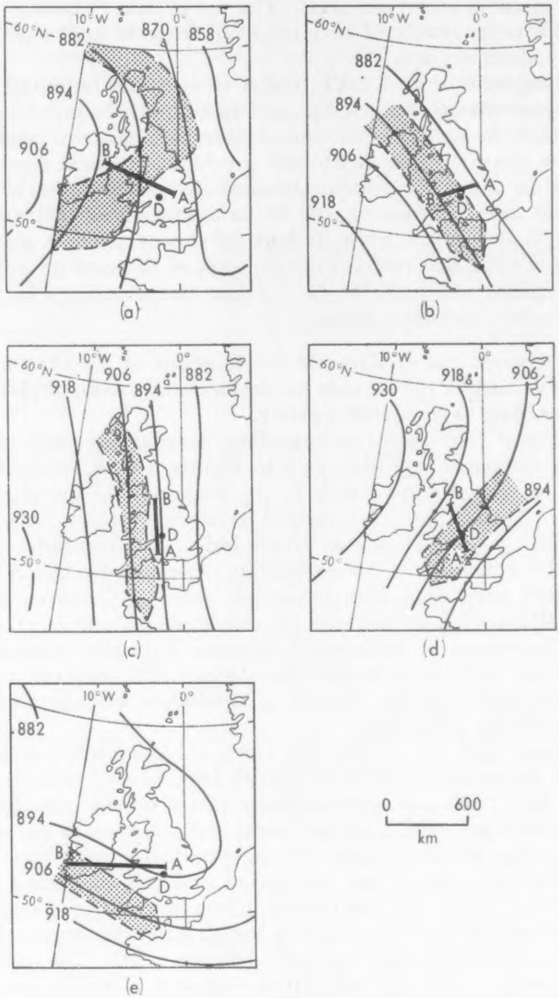

FIGURE 1—APPROXIMATE LOCATIONS OF CROSS-SECTIONS (AB) PRESENTED IN FIGURES 2–7 RELATIVE TO THE JET CORE

(a) 12 GMT on 6 Feb. 1970, system velocity 12½ m/s at 300°,
(b) 00 GMT on 19 Feb. 1971, system velocity 6 m/s at 250°,
(c) 12 GMT on 23 Nov. 1971, system velocity 12 m/s at 355°,
(d) 12 GMT on 24 Nov. 1971, system velocity 10 m/s at 340°,
(e) 12 GMT on 10 May 1972, system velocity 17½ m/s at 270°.

The stippled arrow represents the core of maximum winds. The limits of the jet core are defined as being where the wind speed falls 5 m/s below core maximum. Heights of the 300-mb contours are in decametres. A denotes location of the earliest radiosonde at launch, B that of the last of the period; D shows location of Defford/Pershore.

centre of this system was in mid Atlantic at about 55°N and south-east of the centre was a very wide warm sector. The main warm front lay just west of Cork and the Scillies at 06 GMT on 19 February. On earlier charts there had been some evidence of a weak preliminary warm front with a similar orientation (north-north-west to south-south-east) lying about 600 km ahead of the main warm front. The stable regions associated with both warm fronts show up well in the $\Delta\theta/\Delta z$ analysis in Figure 3 (c), the weak front featuring as the roughly horizontal stable layer at 4 km. The jet core advanced east-north-eastwards to be overhead at Defford at 2130 GMT (Figure 1 (b)). Maximum wind speeds within the core were 70 m/s and both the billow events observed, (crest-to-trough amplitude 500 m) occurred within very strong shear regions (Figure 3 (b)), one just above the jet core and the other just below. One patch of billows occurring at 0115 GMT at a height of 8·3 km and with amplitude of 800 m was associated with a thick cirrus cloud layer and hence is not counted as true CAT.

(c) *23 November 1971* (09 GMT to 18 GMT). A warm front approached western Scotland from the Atlantic and by 18 GMT lay north-south at about 15°W. A northerly jet covered the British Isles. The section (Figure 1 (c)), (assuming a mean system movement of 12 m/s at 355°), was in an area of straight contours between ridge and trough. The west-to-east component of jet movement in the latitude of Defford was minimal, very slight fluctuations in its position resulting in observations being commenced just on the cold side and moving into the core region itself at about 10 GMT, reverting back to just on the cold side by 17 GMT. At no stage was the section more than 100 km from the core centre. Zones of strong shear and stability (Figures 4 (b), (c)) descended from 7 km to 6 km in height during the period and are almost certainly associated with the slowly approaching warm front. Large-amplitude KH billows were observed for several hours after 09 GMT. They occurred in strong and persistent regions of shear and stability below the main frontal zone. The 800-m crest-to-trough amplitude of these billows was the greatest observed throughout the periods of the case studies. Their longevity may be due to the orientation of the section with respect to the jet core with the result that the observations were obtained in the same relative location over a long period. Since the billows were advecting southwards at the speed of the winds at their altitude, they may have comprised a train some 100 km in length. However, the

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Notes on Figures 2–6, (a), (b) and (c)

These figures show a series of time–height cross-sections of the atmosphere derived from data from the Pershore sequential radiosonde ascents. Two distance scales appear above each figure. The upper one indicates the equivalent distance along the section assuming the system velocity in the corresponding Figure 1. The other scale gives a measure of the distances of the section from the jet-core axis (+ on the cold side, − on the warm) with a probable error of ±50 km. Arrows at the foot of each set of figures show times of radiosonde data. Crosses represent position, duration and maximum amplitude of KH billows with crest-to-trough amplitudes in excess of 400 metres. In each set of figures the sections are as follows:

(a) Horizontal wind speed, V, averaged over 400 m. Solid lines are isotachs at 10-m/s intervals.

(b) Magnitude of vector vertical wind shear $\Delta V/\Delta z$ over 400 m. Hatched and close-hatched shading correspond to strong and very strongly sheared layers ($\Delta V/\Delta z$ of 5–10 and > 10 m/s per 400 m respectively). **J** indicates the core of maximum winds.

(c) Vertical gradient of potential temperature $\Delta\theta/\Delta z$ over 400 m height. Hatched, close-hatched and solid shading correspond to weak, strong and very strong stability ($\Delta\theta/\Delta z$ of 2–6, 6–10 and > 10 degC per 400 m respectively). **J** indicates the core of maximum winds. The dotted line represents the conventional troposphere.

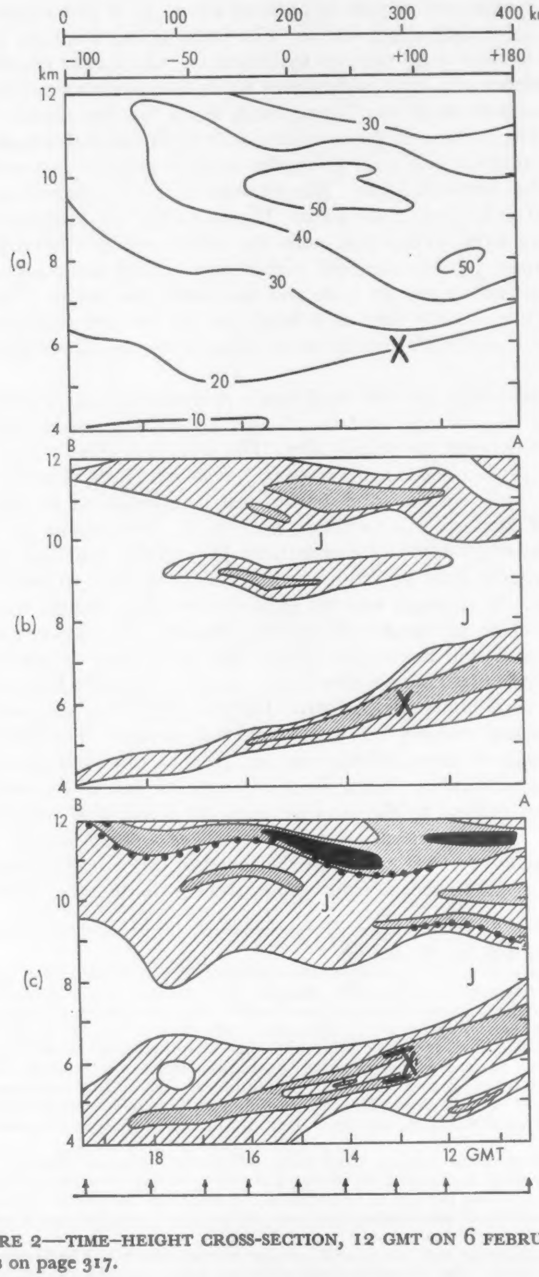

FIGURE 2—TIME–HEIGHT CROSS-SECTION, 12 GMT ON 6 FEBRUARY 1970
See notes on page 317.

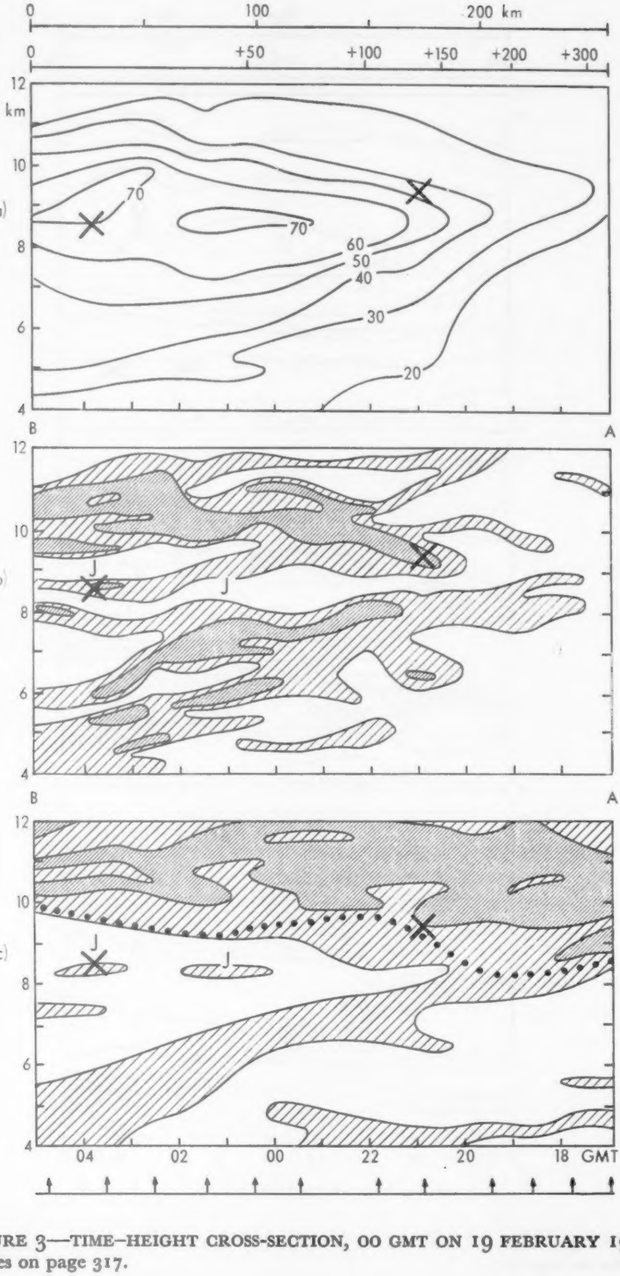

FIGURE 3—TIME–HEIGHT CROSS-SECTION, 00 GMT ON 19 FEBRUARY 1971
See notes on page 317.

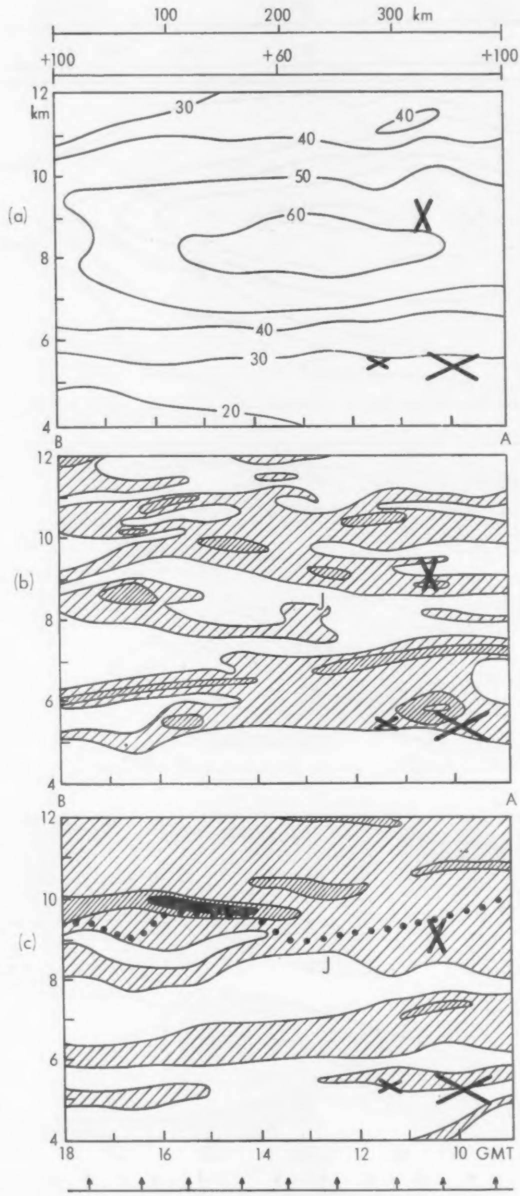

FIGURE 4—TIME–HEIGHT CROSS-SECTION, 12 GMT ON 23 NOVEMBER 1971
See notes on page 317.

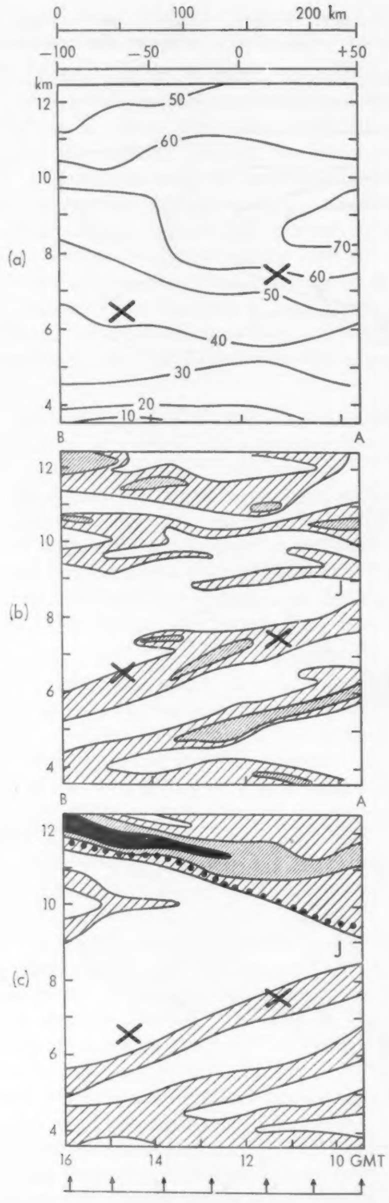

FIGURE 5—TIME–HEIGHT CROSS-SECTION, 12 GMT ON 24 NOVEMBER 1971
See notes on page 317.

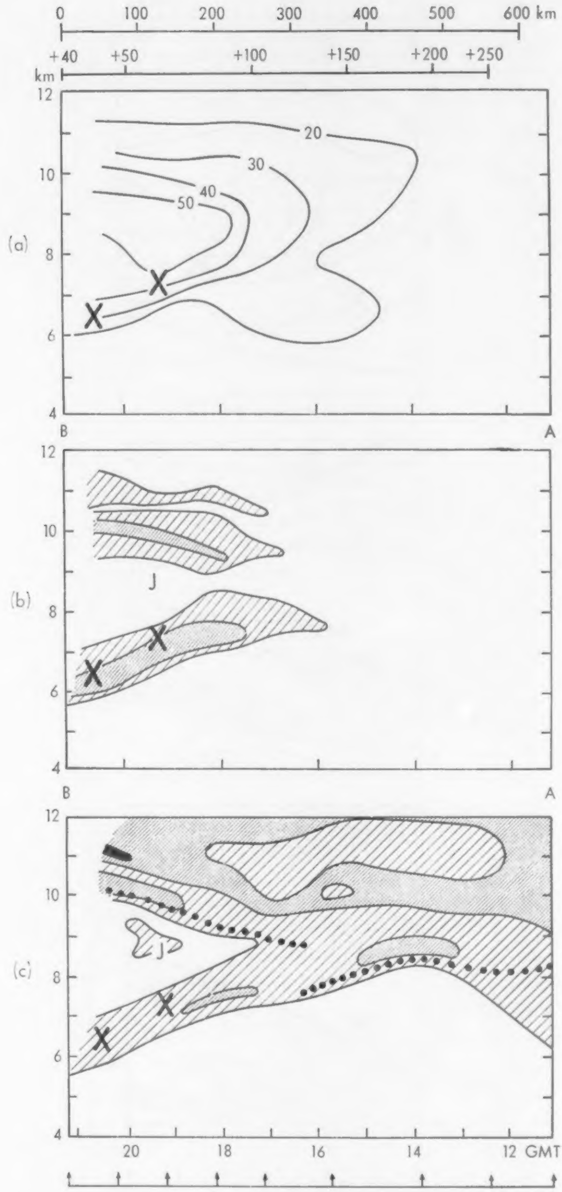

FIGURE 6—TIME–HEIGHT CROSS-SECTION, 12 GMT ON 10 MAY 1972
See notes on page 317.

possibility cannot be overlooked that the billows were initiated just in the vicinity of Defford by minor topographic influences.

(d) *24 November 1971* (0930 GMT to 16 GMT). A warm front oriented north-east to south-west moved rapidly south-eastwards into Scotland. This front was associated with a filling, but deep, depression which moved south-eastwards from Jan Mayen during the period. Behind the front was a broad north-westerly warm sector. A north-easterly jet associated with the front moved south-eastwards across the region (system velocity 10 m/s at 340°). Contours over the Defford area were slightly cyclonically curved. The section was made mainly within the core (Figure 1 (d)) extending into the warm side after 15 GMT and being about 100 km from the jet axis at the end of the period. Winds in the core exceeded 70 m/s. Two tongues of high shear associated with the approaching fronts descended from 6 km at 0930 GMT to $4\frac{1}{2}$ km at 1330 GMT (Figure 5 (b)). The corresponding well-marked stable zones are seen in Figure 5 (c).

Two KHI 'events' were recorded, with amplitudes in excess of 400 m. The two large-amplitude billows were detected by the radar at 1110 GMT at a height of 8 km and occurred within the upper frontal zone.

The Roach Index, Φ (Figure 7 (b)), attained a maximum over Defford before 12 GMT and the two billow events occurred in a region of maximum Φ which lowered and weakened with time in association with the passage of the twin frontal zones. In the next six hours the maximum in Φ at 300 mb was computed to move south-eastwards over northern France and decline, the movement of a corresponding area of CAT being corroborated by turbulence reports from pilots (Brown[9]).

(e) *10 May 1972* (11 GMT to 21 GMT). A cold front lying south-south-west from a small depression in the Channel progressed eastwards during the period. A further frontal system was approaching western Ireland towards the end of the period by which time the general north-westerly wind at low level over much of England and Wales was giving way to a weak ridge moving slowly in from the west. A sharply diffluent upper trough over the north-eastern half of the British Isles pushed south-eastwards into Europe while a north-westerly jet associated with the approaching Atlantic frontal system extended steadily across the south-western half of England. The contour pattern showed slight anticyclonic curvature at the start of the period but became straighter subsequently. The system moved from 270° at $17\frac{1}{2}$ m/s. An initial rise of the stable layer at about 8 km on the $\Delta\theta/\Delta z$ section (Figure 6 (c)) is probably associated with the receding cold front. Thereafter the lowering ahead of the warm front approaching Ireland is sharply defined. The section was made from the cold side of the jet, entering the core at 1740 GMT (Figure 1 (e)). Until about 16 GMT the wind speed was less than 30 m/s. Figure 6 (b) shows that, as the jet core approached, the horizontal and vertical velocity gradients tightened considerably; at $8\frac{1}{2}$ km the wind speed increased by 20 m/s in the hour 17 to 18 GMT. The implied cyclonic shear during this period was an order of magnitude greater than the Coriolis parameter. Billow echoes were absent until at least 16 GMT (when the radar surveillance was interrupted for servicing) and probably until 1810 GMT since only one minor layer echo (at a height of $4\frac{1}{2}$ km) was detected when radar observations were resumed at this time. This assumption is supported by data from the 1708 GMT radiosonde which did not show any

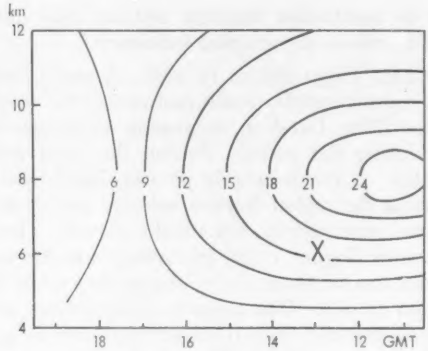

FIGURE 7 (a)—THE ROACH INDEX, Φ, APPLIED TO FIGURE 2
Units are expressed in 10^{-5} s^{-1}.

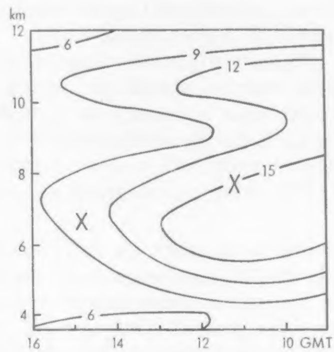

FIGURE 7 (b)—THE ROACH INDEX, Φ, APPLIED TO FIGURE 5
Units are expressed in 10^{-5} s^{-1}.

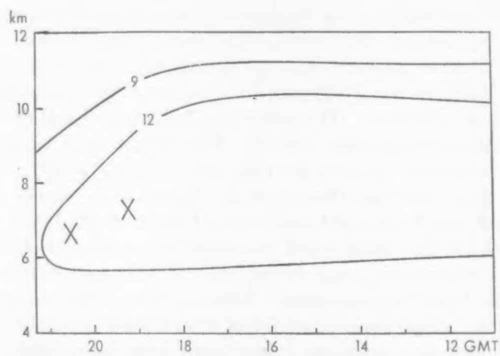

FIGURE 7 (c)—THE ROACH INDEX, Φ, APPLIED TO FIGURE 6
Units are expressed in 10^{-5} s^{-1}.

regions where $Ri < 0{\cdot}5$. A well-marked region of CAT developed within the frontal zone soon after 18 GMT. Over a $2\frac{1}{2}$-hour period the layer lowered, following the slope of the frontal zone, and two occurrences of large-amplitude KH billows were observed.* Both billow trains occurred within a region where the Roach Index was in excess of $12 \times (10^{-5}\,s^{-1})$ (Figure 7 (c)).

Discussion. During the 40 hours of radar observations comprising the case-studies large-amplitude billow echoes (crest-to-trough amplitude in excess of 400 m) were detected for about 5 hours, i.e., as much as 12 per cent of observing time. It is important to remember, however, that periods of observation were deliberately chosen to be during periods considered favourable for the development of CAT.

Table I presents the number distribution of the large-amplitude billows as a function of shear, stability and Richardson number.

All 10 large-amplitude billows occurred in regions of low *Ri* and strong shear; indeed 7 of the billows developed under the conditions of low *Ri* and very strong shear (as defined formally in the Introduction). It would appear, then, that the 400-m vertical resolution with 1-hour time spacing of the sequential radiosonde data is adequate to resolve the mesoscale features responsible for all large-amplitude KH billows.

The detailed time–height sections derived for each of the case studies, demonstrate the existence of mesoscale regions of relatively strong shear and stability embedded within the synoptic scale zones (as described also by Barbé[11]) which may be responsible for the patchy occurrence of CAT (smaller-scale regions may be generated by previous occurrences of CAT; Browning[12]). Inspection of the time–height sections reveals, however, that suitable combinations of very strong shear and low *Ri* do occur quite often without billows being observed in the vicinity of Defford. It should be remembered that the CAT observations were obtained from a single site covering a range of typically 15 km. Billows may have occurred within the layers of suitable ΔV and *Ri* when just out of range of the Defford radar.

A brief statistical interpretation of the data is presented in the form of histograms of the frequency of occurrence of certain mesoscale features derived from data from the 46 radiosonde ascents made during the five case studies. Figure 8 depicts the depth overhead of regions of strong stability. It shows that almost 50 per cent of these layers had a vertical half-width of less than 1 km while about 30 per cent of the layers had a vertical half-width of more than 2 km; these regions occurred mainly near the tropopause. The corresponding histogram for the depth overhead of very strong shear regions is portrayed in Figure 9. The vertical half-width of 66 per cent of these layers was less than 1 km, the modal value being 400 to 600 metres.

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* During these periods of KH billows, information from the high-power radar display permitted the instrumented Canberra of the Meteorological Research Flight to be directed into the billows. Simultaneous records of Doppler radar measurements of the billow pattern and aircraft response were obtained, the aircraft reporting moderate to severe turbulence as it encountered the well-defined billow train at 1910 GMT. These and other results of a joint CAT Study Programme run by the Meteorological Office Special Investigations Branch, the Meteorological Research Unit, Malvern and the Meteorological Research Flight, Farnborough have been evaluated (see for example Browning, Bryant, Starr and Axford[10]).

TABLE I—THE OCCURRENCE OF LARGE-AMPLITUDE KH BILLOWS AS A FUNCTION OF SHEAR, STABILITY AND RICHARDSON NUMBER

Event	Date	Height *km*	Duration GMT	*min*	Minimum crest/trough amplitude *m*	Δv $m\ s^{-1}(400\ m)^{-1}$	$\Delta\theta$ $degC(400\ m)^{-1}$	*Ri* (For a 400-m deep layer)
(a)	6 February 1970	6·0	1245–1300	15	400	13·5	6	0·4
(b)	18–19 February 1971	9·5	2040–2116	36	500	14·8	6·4	0·3
		8·5	0326–0400	34	500	10·5	2·4	0·2
(c)	23 November 1971	9·0	1025–1040	15	800	11·5	2·6 to 5·8	0·5
		5·5	1120–1150	30	400	8·5	2·8	0·4
		5·5	0910–1035	85	800	14·5	2·5	0·5 to 0·1
(d)	24 November 1971	7·7	1100–1130	30	400	9·2	3·8	0·2
		6·7	1425–1450	25	400	6·5	1·2	0·1
(e)	10 May 1972	7·2	1905–1925	20	400	16·0	5·9	0·3
		6·5	2020–2040	20	500	14·2	5·1	0·3

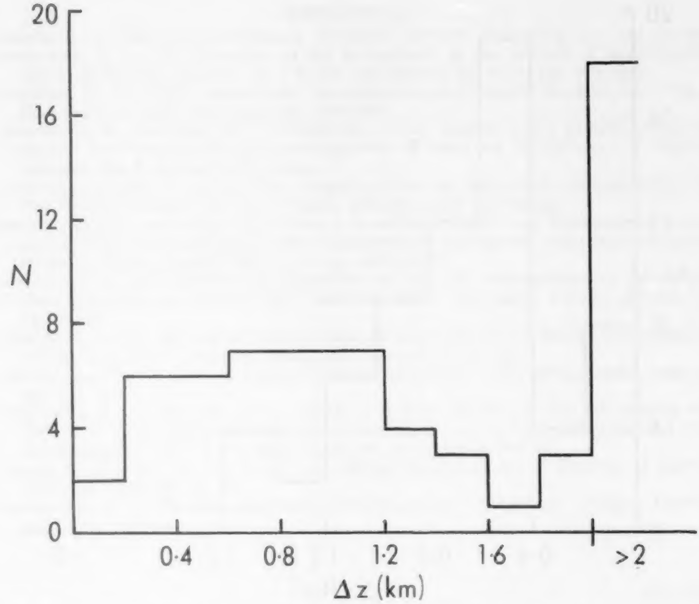

FIGURE 8—NUMBER DISTRIBUTION, N, OF THE VERTICAL HALF-WDITH, Δz, OF LAYERS OF STRONG POTENTIAL TEMPERATURE GRADIENT (IN EXCESS OF 6 degC PER 400 m)

Data are derived from a total of 46 radiosonde ascents obtained during the five case studies.

The sections of Roach Index are probably subject to larger errors owing to the coarse scale of the input data. They do, however, present the billow events as occurring near maxima of Φ and, in particular in regions of the sections where $\Phi > 10 \times (10^{-5}\ s^{-1})$. This is in line with case studies by Brown[9] based on aircraft reports of turbulence.

Tables (not presented) were drawn up to display the percentage area of the time–height sections, averaged over the five studies, which were occupied by large-amplitude billows and by regions of very strong shear and low *Ri*. Estimates were tabulated relative to the position of the jet core. Very strong shear regions occupied about 5 per cent of the area of the time–height sections from 1 km above to 5 km below the jet core and in the range 100 km on the warm side to 200 km on the cold side of the jet core. Large-amplitude billows occupied about 25 per cent of these very strong shear regions between 1 and 3 km below the jet; elsewhere the percentage was much less with an average of about 12 per cent for the section as just defined for the very strong shear regions. The maximum percentage area coverage for regions of low Richardson number occurred within the layer between 1 and 3 km below the axis of the jet and within the column between the axis of the jet and 50 km on the cold side. Large-amplitude billows occupied on average about 4 per cent of these regions of low *Ri* between 1 km above and 5 km below the jet core and from 100 km on the warm side to 200 km on the cold side of the jet core. A maximum

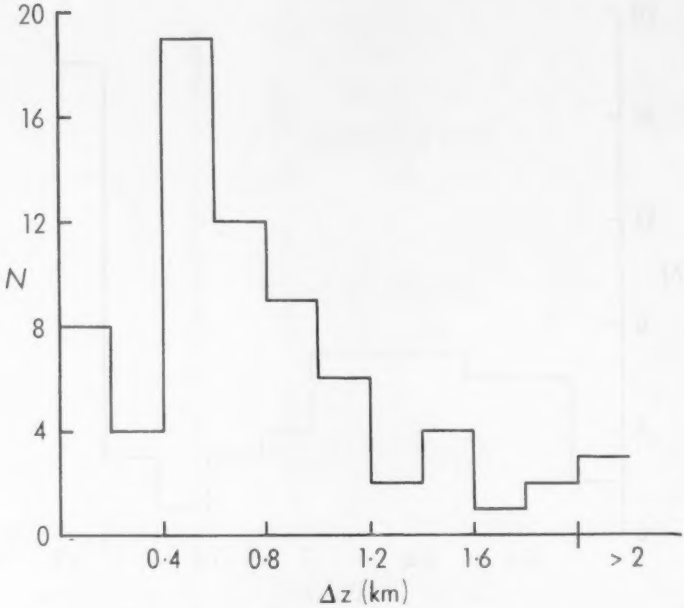

FIGURE 9—NUMBER DISTRIBUTION, N, OF THE VERTICAL HALF-WIDTH, Δz, OF VERY STRONGLY SHEARED LAYERS (MAXIMUM SHEAR IN EXCESS OF 10 m/s PER 400 m)

Data are derived from a total of 46 radiosonde ascents obtained during the five case studies.

of 10 per cent occurred between 1 and 3 km below the jet between the range limits mentioned above. Large-amplitude billows occupied an average of about 10 per cent of areas where conditions of very strong shear and low *Ri* coexisted.

In conclusion, therefore, it can be said that cross-sections of ΔV and $\Delta\theta$ demonstrate that mesoscale structures responsible for all the observed large-amplitude KH billows can be defined by a sequence of radiosonde ascents. Limitations of fixed-point observations preclude a definite statement as to whether or not CAT occurred within all seemingly suitable mesoscale structures. It seems unlikely, though, that CAT identification based even on hourly radiosonde data such as those presented here, could be framed in other than probability terms.

Acknowledgements. The authors wish to thank the following Meteorological Research Unit personnel for their contributions as listed: Messrs A. J. Whyman, D. M. Parkes and J. A. Reeve (operation of Defford radar), Messrs S. R. Smith, R. M. Timms, A. C. Windmill, R. J. Stephens and M. Bristow (special radiosondes). Helpful suggestions were made by Mr S. G. Cornford and Dr W. T. Roach.

The Defford research programme is undertaken under the direction of Dr K. A. Browning.

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THE METEOROLOGICAL OFFICE WEATHER OBSERVING SYSTEM (MOWOS) Mk 2

By G. J. DAY, K. J. T. SANDS and B. TONKINSON

Summary. The trial of the Automatic Weather Station (MOWOS Mk 2) is discussed followed by a technical description of the system. Sensors in current use are described and the problems associated with maintenance of remote stations outlined.

Introduction. Between 1965 and 1969, the Meteorological Office conducted experiments with Automatic Weather Stations which featured a range of new sensors and an analogue telemetry and display system. By 1968 it was apparent that both the telemetry system and the meters used in the display console were sources of unacceptable errors, and proposals were made for a new system based on digital stores, telemetry and displays. The new system became known as the Meteorological Office Weather Observing System Mk 2 (MOWOS).

By the end of 1969 approval had been given for the establishment of a pilot network of 8 MOWOS stations in order to assess the overall effectiveness of the new system before proceeding to a larger network. However, it was not until early in 1971 that all the details of the scheme had been settled and approval given for the procurement of 10 sets of equipment. Of the 10 sets 2 were intended for further development work and training.

From the placing of the contract with Hawker Siddeley Dynamics Ltd, work at the contractors and in the Operational Instrumentation Branch was carried out in accordance with 'Programme Evaluation Review Technique' (PERT) diagrams and regular project control meetings were held. It is to the credit of all concerned that the first set of equipment was delivered to the

Experimental Site at Beaufort Park on the day specified at the placing of the contract.

After three months of testing, which led to some minor modifications, the go ahead was given for production and the Contract completed in May 1974. Three sets have so far been installed, at Beaufort Park, South Farnborough and Leuchars, and it is hoped to complete the programme when permission is given for the resumption of works services at the remaining six sites.

When complete, it is expected that the pilot network of 8 MOWOS field stations and associated receiving stations will be similar to that shown in Figure 1. Positions are chosen by the Meteorological Office's Working Group on United Kingdom Observational Networks to be representative of a wide variety of meteorological and operating environments, in order that an assessment can be made of all aspects of the performance of the equipment.

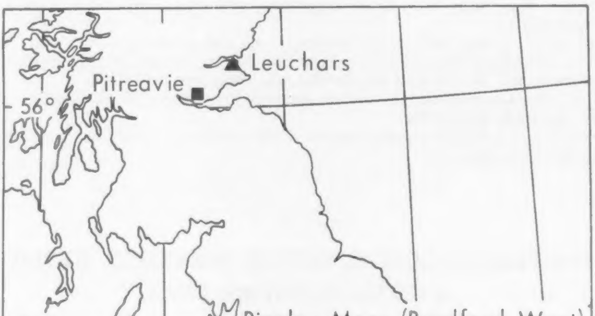

FIGURE 1—PROPOSED PILOT NETWORK OF MOWOS REMOTE AND RECEIVING STATIONS

▲ Remote station ■ Receiving station.

In succeeding sections, the MOWOS system is described and some general comments are made on the role of automatic systems in observational networks.

MOWOS

The remote field station. The remote station accepts the output from the sensors, processes and stores the data and transmits them on demand to the receiving station. Data are transmitted over the public switched telephone network, using the DATEL 400 Service. Stations are located, when possible, to take advantage of Subscriber Trunk Dialling (STD).

Figure 2 shows the layout of the standard MOWOS remote station. The layout conforms to the normal recommendations on exposure of sensors. The data-processing circuits are housed in a weatherproof shelter in the shape of a cube having sides about 2·5 m in length. The walls are well insulated and thermostatically-controlled heaters are provided to maintain the interior of the shelter at a constant temperature of about 20°C. The shelter contains benching and facilities for personnel working on the system during routine or emergency servicing visits. However, experience so far is that servicing in the field is minimal and consideration is being given to redesign of the remote station to facilitate servicing by module replacement.

Output from the meteorological sensors can be of either analogue or digital form. Analogue outputs are converted by interface circuits to a d.c. voltage in the range 0 to 5 volts. The 12 analogue data channels are sampled sequentially at 5-minute intervals and the corresponding voltage converted to 10-bit binary words which are passed through a serial working store into a serial transfer store. If the remote station is interrogated during data transfer, a reply is inhibited until the transfer is complete.

For sensors having a digital output, channels are allocated to specific sensors. Digital information is passed directly from the sensor into the working store and thence into the transfer store at intervals of 5 or 10 minutes depending on the integration time appropriate to the particular sensor.

A group of channels is also used to monitor three precision voltages in the data-processing system, the presence or absence of other critical voltages and the temperature in the shelter.

The remote station contains an accurate quartz crystal clock which provides a precise time for each message and also control pulses for the data-processing system.

Reception of an interrogation signal from the receiving station initiates the following, automatic, sequence of events at the remote station.

(a) A check is made to determine whether data are being transferred into store.

(b) Further transfer of data from the working store is inhibited.

(c) A signal is sent to the receiving station indicating, by a light, that the remote station is ready to transmit data.

(d) Operation of a 'data' switch at the receiving station initiates the transfer of the contents of the store to a data highway.

(e) Data are transmitted, preceded by fixed synchronizing words, the station number and the time when the store was last updated. The complete message, or frame, comprises 32 10-bit words.

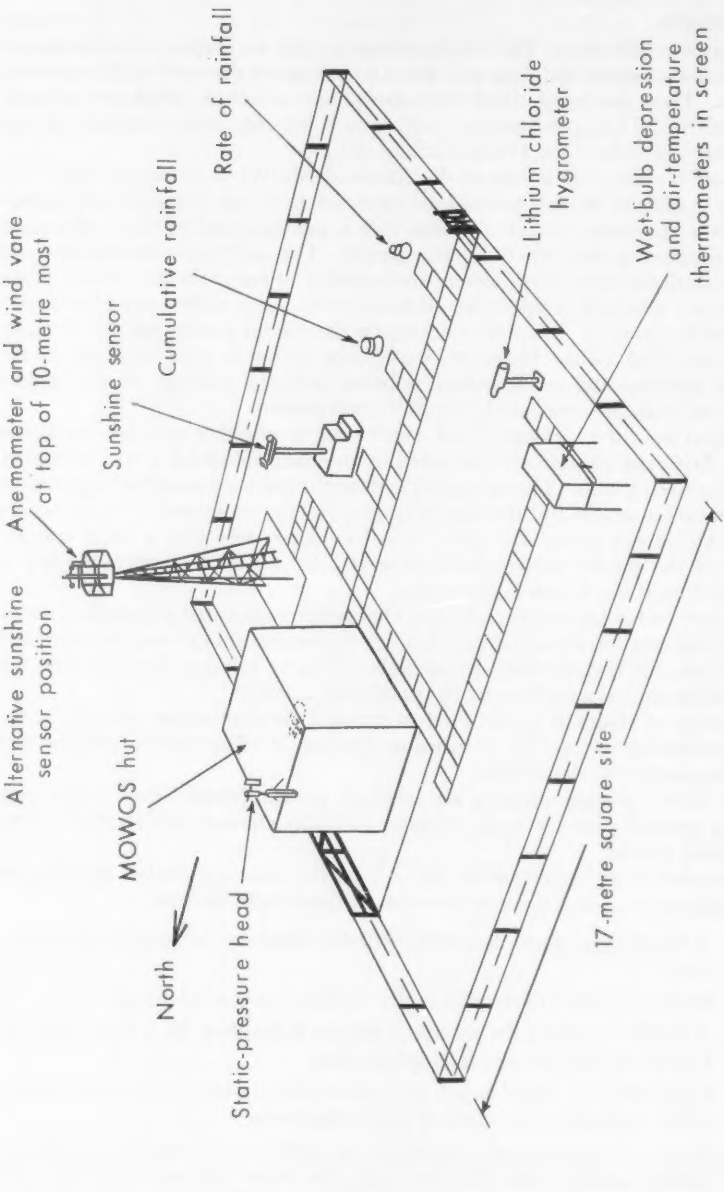

FIGURE 2—MOWOS REMOTE STATION

(f) Complete frames are repeated, up to eight times and compared word by word at the receiving station. When agreement between corresponding words is achieved, the transmission is terminated. Transmission of eight frames takes 52 seconds but it is rare for more than three frames to be needed to establish parity, that is about 20 seconds from initiating a transmission. Parity checking is described below.

The receiving station. The receiving station is housed in a single-pedestal desk and is illustrated in Figure 3.

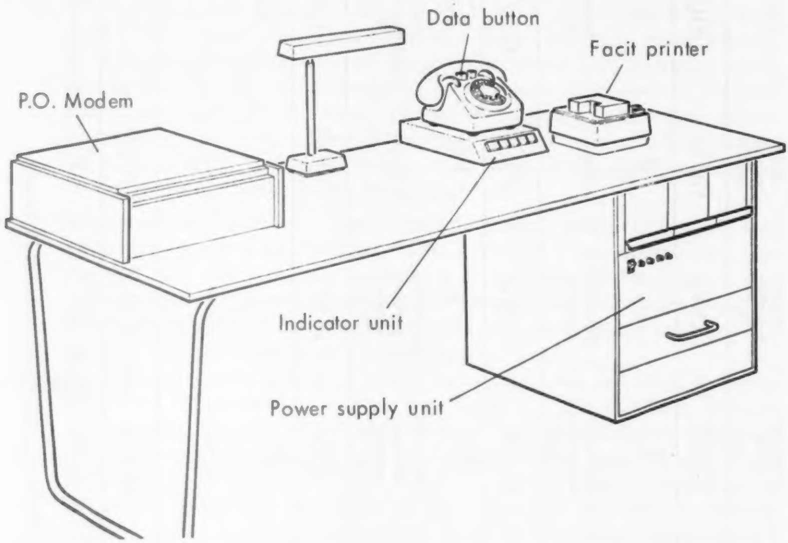

FIGURE 3—MOWOS RECEIVING STATION
Modem is an acronym for modulator and demodulator unit.

When contact with the remote station has been established, two complete frames of data are passed to shift registers and compared bit by bit. Each complete word for which parity is established is passed to a data store in the receiving station and the number of words in the store counted. Successive frames of data are passed into the shift registers, overwriting the oldest frame stored, until 32 words are counted in the data store. Five attempts to establish parity can be made, using 7 complete frames of data; the first frame is always discarded but parity is almost invariably established with the third frame. If parity is not established, an audible and visible alarm is given. Once a complete frame of data is stored, an indicator lights up showing that the telephone handset should be replaced. Replacing the handset disconnects the remote station and initiates the serial transfer of the data from the store. A conversion is now made from the binary code, hitherto used throughout the system, to teletype code and the data are printed by the strip printer. The message is a series of 4-digit words and an elementary code is used which is closely related to engineering units. A typical message is shown in Figure 4.

Word number		
1	Station identity (677)	0677
2	Time hours (1630 GMT)	0016
3	Time minutes (1630 GMT)	0030
4	Sunshine (38 s)	0038
		=
5	Wind direction (40°)	0040
6	Wind speed (16 kt)	0016
7	Blank	0000
8	Rate of rainfall (5 mm/h)	0050
9	Cumulative rainfall 64.2 mm	= 0321
10	Pressure (985.0 mb)	0425
11	Dry bulb (11.0°C)	0410
12	Wet-bulb depression (2.0 degC)	0020
		=
13	Dew-point (6.8°C)	0368
14	Blank	0000
15	Station identity	0677
16	Time hours	0016
17	Time minutes	= 0030
18	Shelter temperature (20.0°C)	0500
19	+15 volt precision supply	307
20	Positive battery supply (+20 V)	409
		=
21	Negative battery supply (−20 V)	409
22	Blank	0000
23	Dewcel inverter supply off/on (on)	0000
24	Sensor supplies off/on (on)	0000
25	+15 volts supply off/on (on)	= 0000
26	−15 volts supply off/on (on)	0000
27	Blank	0000
28	Blank	0000
		=
29	Blank	0000
30	Blank	0000
	End of message	= = =

FIGURE 4—TYPICAL MOWOS MESSAGE FORMAT

The meteorological sensors. MOWOS has been designed to be compatible with standard Meteorological Office sensors, as far as possible, but some of the sensors are currently used only with automatic systems.

The primary sensor suite is as follows:

(a) Wind speed is measured with a Meteorological Office Mk 4 anemometer. A switch in the anemometer closes every 50 revolutions of the cup rotor and the switch operations in a 10-minute period are counted to give a mean wind speed.

(b) Wind direction is measured with a Meteorological Office Mk 5 wind vane.[1] The magslip is energized from a three-phase a.c. power supply, the phase relationship between the magslip output and its supply being proportional to the wind direction. The phase difference is detected and converted to a d.c. voltage varying from 0 to 5 volts. This voltage is averaged[2,3] to give a 10-minute mean wind direction which is converted to digital form and stored. The form of averaging used gives most weight to events late in the period.

(c) Pressure is measured with an aneroid capsule which moves an iron armature within a transformer. This differential transformer is incorporated in a circuit which produces a d.c. voltage in the range 0 to 5 volts and which also compensates for temperature deviations from the standard value obtaining during calibration. A pressure range of 900 to 1050 mb is covered with a resolution of 0·2 mb.

(d) Temperature, wet- and dry-bulb, is measured with 100-ohm platinum resistance thermometers to BS 1904 Grade I. The dry-bulb thermometer forms one arm of a Kelvin Bridge, the out-of-balance voltage of which is amplified to give a d.c. voltage in the range 0 to 5 volts, representing temperatures from -30 to $+40$°C with a resolution of 0·1 degC. Wet-bulb depression in the range 0 to 12 degC is similarly obtained by comparing wet- and dry-bulb thermometer resistances in a Kelvin Bridge.

(e) Dew-point temperature is measured using a lithium chloride hygrometer—often referred to as a 'dew-cell'. This sensor incorporates a platinum resistance thermometer whose resistance is measured with a Kelvin Bridge as in (d) above. The temperature indicated is closely related to the dew-point but small corrections have to be applied, e.g. one for non-linearity and one which is a function of relative humidity. The dew-cell is used to provide dew-points in freezing conditions below 0°C when the wet- and dry-bulb psychrometer is inoperative.

(f) Cumulative rainfall is measured with a Meteorological Office 750-cm^2 collector and tipping-bucket switch. Each operation of the switch corresponds to an increment of 0·2 mm of rain and is used to increase the count in the data store. The store is reset when 1023 bucket operations have been counted. In some circumstances tests of the system by servicing personnel may cause the counter to reset before the value 1023 has been reached.

(g) Rate of rainfall is measured with a drop-counting system. A calibrated orifice attached to a 750-cm^2 collector forms drops of uniform volume which interrupt a light beam as they fall. An associated circuit causes

the varying output of a photo-electric detector to operate a reed switch, and the number of switch closures in 5 minutes is counted to provide the average rate of rainfall in the period.

(h) Duration of bright sunshine is measured with a recently developed sensor.[4] Two matched thermistors are embedded in 5-mm diameter matt-black phosphor-bronze spheres, and each is mounted at the centre of a sealed perspex hemisphere of 10 cm diameter and containing dry air. One thermistor is exposed to the direct sun and the other protected from it by a shade ring. The temperature of each thermistor is a function of the ambient temperature and of the incident radiation. When there is bright sunshine, a difference of temperature is established between the two thermistors which is detected by an associated circuit and used to operate a reed switch. A train of regular pulses is counted when the switch is closed and the number of pulses in 10 minutes is converted to give the number of seconds of bright sunshine during the period.

The design of the shade ring is a compromise. A broad ring reduces the risk of direct radiation reaching the shaded sphere, and also reduces the need for adjustments of the ring as the sun's altitude varies through the year. Too broad a ring, however, causes less sky radiation to reach the shaded sphere than that reaching the exposed one and in a few cases this could lead to false indications of bright sunshine.

The sunshine sensor is intended as a crude indicator of cloudiness, but the correlation between duration of bright sunshine and total cloud amount is not very high.

Care of the system. Care of the MOWOS remote station falls into two parts:

(a) 'Housekeeping' attention; this is provided by a local caretaker who is engaged to visit the site several times each week. During each visit the site is inspected for damage or obvious malfunctioning of equipment, the grass is cut when necessary and rain-gauges checked for blocking by leaves, insects or bird droppings. Check observations are made of wet and dry-bulb temperature and pressure, and these are telephoned to the Parent Receiving Station. Approximately once a month the screen is washed. Wet-bulb reservoirs are replenished and the wicks changed when appropriate.

It is intended to reduce the number of housekeeping visits in the light of experience, perhaps to about one visit a week. In the growing season, grass cutting may dictate a minimum frequency but regular visits will continue to be required since the sensors are the least reliable part of the system.

(b) Servicing visits are made by technicians of the Regional Servicing Organization every two months to 'redope' the lithium chloride hygrometer. Every six months, sensors are calibrated with portable apparatus and the electronic system checked by the injection of test signals from a sensor simulator developed in the Meteorological Office. Current evidence is that the mean time between failures (MTBF) for the data-handling system will be excellent, possibly as much as 1 year.

Conclusion. MOWOS is a modern data-acquisition system which has been designed to provide meteorological data with an accuracy comparable with that achieved by the human observer using conventional instrumentation. It has been designed for high reliability even when the data are transmitted over poor-quality telephone circuits.

MOWOS was conceived as a synoptic meteorological system but there is provision for the later addition of a data logger should the data prove to be of an acceptable standard for climatological purposes. The principal use envisaged for the system is the acquisition of data from sites where it is not possible to use human observers, or at times when they are not available. It can therefore be used to fill network gaps in both time and space and, for instance, MOWOS might take over from an observer when a station is unmanned.

The human observer is still essential for such non-instrumental observations as cloud type and present weather. However, if purely instrumental data are acceptable, it has been calculated that MOWOS observations cost only half those of human observers, on a 24-hour basis. MOWOS provides the opportunity to fill the gaps in the present network, and it is possible that a hybrid network will emerge in which man and machine perform complementary rather than overlapping activities.

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CLIMATE AND FOOD PRODUCTION

One outstanding feature of the *weather* in most parts of the world is its variability; tomorrow it may be much warmer than today, next winter may be much wetter than last winter. But when we speak of the *climate*, which is usually considered as the average weather at a given place over a period of 10 years or more, we tend to think of something which is fairly stable. In fact, however, the climate does fluctuate from one decade to the next and there are longer-term trends in climate from one century to the next. For example, there is some evidence that the average temperature of the northern hemisphere rose by about 0·6 degC between 1900 and 1940, since when it has fallen again by about 0·3 degC. These changes may seem very small but they can be very important for agricultural production, especially in marginal areas where the changes may in any case be somewhat larger than the average change for the whole hemisphere. At the present time when the world has difficulty in

producing enough food for its growing population, and when the grain reserves are already almost exhausted, it is obvious that Man is becoming more sensitive to fluctuations in weather and climate.

The July number of the *WMO Bulletin* contains two articles which are relevant to the above concerns. In 'World Weather Watch and wheat', a Canadian agricultural meteorologist, George W. Robertson, describes how predictions of the yield of wheat in any year can be made more accurately with the help of weather data. Such predictions are of course of great value for agricultural and economic planning. In 'Fluctuations of climate—monitoring and modelling', Professor John Kutzbach of the University of Wisconsin reviews the changes and the steps which must be taken to improve our understanding of climate.

Leading scientists from about 15 countries met in Stockholm from 29 July to 9 August this year to discuss our present knowledge of the theory of climate. This conference was convened by the World Meteorological Organization and the International Council of Scientific Unions within the framework of the Global Atmospheric Research Programme and with support from the United Nations Environment Programme. Special attention was given to the development of improved mathematical models of the atmosphere which, with the aid of powerful computers, can be used to assess the long-term response of the atmosphere–ocean–land system to changes in any of the basic factors which determine climate. Reports were presented on experiments made with such models to compute, for example, the effect of a change in solar radiation, an increase in the carbon dioxide in the atmosphere and an increase in atmospheric pollution. Further work on atmospheric models should help to improve our understanding of the mechanisms which are responsible for climatic change, both natural and man-made.

Most scientists would agree that, in view of the growing economic and social impact of year-to-year variations in weather and of any long-term trends in climate, a major international scientific effort is called for in order to determine whether such variations and trends can be predicted. WMO is now giving increased attention to these questions.

WMO PRESS RELEASE

NOTES AND NEWS

Retirement of Mr L. Sugden

On 3 November 1974 Mr Leo Sugden retired from the Meteorological Office, where for the past four years he held the post of Assistant Director, Public Services.

Mr Sugden gave up teaching to join the Office in April 1940. Before the end of that year he became an independent forecaster at Headquarters No. 11 Group, RAF Uxbridge, and started on a career during the whole of which he has been closely associated with forecasting, especially for aviation. During the latter part of the war he served in the Second Tactical Air Force and then in British Armed Forces Overseas, Germany. After demobilization he returned to Germany as a forecaster until late 1950.

For 14 years he was a senior forecaster at London/Heathrow Airport, receiving substantive promotion to Principal Scientific Officer in 1952. This period saw a great expansion in civil aviation, and Mr Sugden played an active part in the development of forecasting techniques for transatlantic flights.

In November 1964 he turned from forecasting to administration when he took charge of the Main Meteorological Office at the Air Traffic Control Centre, Uxbridge. His aptitude for this type of work led to his posting to the civil aviation section of the Public Services Branch at the Headquarters of the Meteorological Office in Bracknell. Here he maintained excellent relations with the various civil aviation authorities and represented the United Kingdom at numerous meetings and Working Groups of the International Civil Aviation Organization.

On 1 January 1971 Mr Sugden was promoted to Senior Principal Scientific Officer to take charge of the Public Services Branch, where his responsibilities included the weather centres and meteorological services to industry and the public as well as civil aviation. He continued to be much involved in international matters; in the past year he was the United Kingdom delegate at a World Meteorological Organization Commission for Aeronautical Meteorology session in Montreal, and he took part in difficult negotiations at several meetings in Europe concerning the future of ocean weather stations.

We all wish Mr and Mrs Sugden many years of happy retirement.

M. H. FREEMAN

Remote Sensing Society conference

The Remote Sensing Society held its first general conference on 17–19 September 1974 at the University of Aston, Birmingham. The conference discussed the evaluation of the application of space platforms, resource surveys, remote sensing of the environment and remote-sensing data processing. A few papers were relevant to the interdisciplinary branches of applied meteorology such as agricultural meteorology.

REMOTE SENSING SOCIETY PRESS RELEASE

Comparisons of rainfall at Kew

Comparisons of rainfall measured at Kew indicate that, compared with the gravimetric rain-gauge,* the standard 5-inch rain-gauge and the World Meteorological Organization reference pit gauge undercollect by about 5 per cent and 2 per cent respectively. A detailed paper on these comparisons will be published shortly.

* CRAWFORD, S. G.; A recording gravimetric rain-gauge—towards an absolute instrument. *Met Mag, London*, **101**, 1972, pp. 368–374.

Automated weather radar display

A system developed under the auspices of the Weather Radar Planning Group for digitizing weather radar information, transmitting it in real-time over an ordinary telephone line, and displaying it on a colour television screen with different colours representing different rates of rainfall was successfully demonstrated in the Central Forecasting Office on 12, 13 and 14 March 1974.

For an article on this subject see the June 1974 issue of *Weather*;* a colour photograph appears on the cover.

The PDP 11/40 mini-computer

The Digital Equipment Corporation PDP 11/40 mini-computer, has been delivered to the Meteorological Office Headquarters and has passed its technical trials.

The PDP 11/40 was acquired primarily to convert data recorded in non-standard forms into media acceptable to the main computer installation (currently an IBM 360/195). This is already being done for certain climatological data which are experimentally being recorded automatically on special magnetic-tape cassettes. The new Mk 3 radiosonde will produce much more detailed data than the existing Mk 2b; summaries will be transmitted direct to the Telecommunications Branch for operational use and the full data will be recorded on magnetic-tape cartridges which will be handled by the PDP 11/40.

The collection of data in computer-readable form eliminates chores which otherwise have to be performed manually (e.g. writing down the figures and keying them) and makes the data more quickly available to the user. It is cheaper to record the data in simple, non-standard form and then to convert, rather than to record in a form directly compatible with the main computer.

The PDP 11/40 has been equipped with a wide range of peripherals (e.g. visual display unit and electrostatic printer/plotter) to allow it to handle a variety of experimental problems. Perhaps one of the most interesting experiments is the design of a computer-controlled terminal that could give main meteorological offices, and perhaps outstations, direct access to the data held in the computer at Bracknell and the ability to display and manipulate the data as they choose.

It is intended that the PDP 11/40 should be used as an experimental test-bed for any application which could require a dedicated small computer. In comparison with larger computers it is relatively simple to add new devices to this computer and to deal with events as they happen, e.g. on-line instrument control and data acquisition.

OBITUARIES

It is with regret that we have to record the death of Mr G. Doherty, Senior Scientific Officer, Pitreavie on 14 June 1974, of Mr J. McStuart, Scientific Officer, London/Heathrow Airport on 28 June 1974 and of Mr I. Keenan, Assistant Scientific Officer, Masirah on 30 June 1974.

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* TAYLOR, B.C. and BROWNING, K.A.; Towards an automated weather radar network. *Weather, London*, **29**, 1974, pp. 202–216.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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